



TITLE:

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Shear strength reduction in progress of shear displacement on the landslide near dam reservoir

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Abstract

Landslides may cause enormous human casualties, economic losses, infrastructure damages and the change of physical environment and geomorphology. Landslides on the upstream of dam reservoir obviously occur when reservoir impoundment has affected groundwater level of the upstream slope that penetrates into the susceptible soil layers which can fall down to the reservoir. The falling landslide mass into reservoir would significantly reduce the reservoir capacity as sustainable water resource for human and agriculture needs. The study of shear strength reduction in landslide mass is important as part of the landslide dynamics science which covers mobility after failure associated with landslide hazard level, risk assessment, landslide velocity and affected area. In this paper, the shear strength reduction in progress of shear displacement on the landslide near dam reservoir is obtained by means of ring shear tests. Examined samples were taken from the 2008 deep-seated large-scale landslide near Aratozawa reservoir that is located in Miyagi Prefecture, Japan. The observed data indicated that during eight months before landslide event on 14 June 2008, the Aratozawa reservoir was impounded significantly and caused high pore pressure in the suspected slip surface layer. The undrained cyclic loading tests and earthquake loading tests are conducted to explain the shear strength reduction in progress of shear displacement and high initial pore pressure from pre-failure state to the steady-state motion. The results of the tests implied that the sample from secondary collapse zone was the weakest specimen which is vulnerable to be mobilized in a long distant shear displacement. In addition, the ring shear test results indicated that the rapid shear strength reduction of landslide mass was mainly caused by initial high pore pressure and exacerbated by the 2008 Iwate-Miyagi inland earthquake as a main shock in the case of deep and large-scale landslide near Aratozawa dam reservoir.

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Keywords: Landslide; reservoir impoundment; shear strength reduction; ring shear test

1. Introduction

The term landslide is defined as ‘the movement of a mass of rock, earth or debris down a slope’¹. Landslide occurs particularly on slope where soil strength decreases because of the increment of pore water pressure and finally fails due to disturbance from outside of soil structure. Landslide could take place due to erosion near rivers, rainfall, rapid increase of groundwater level, rapid drawdown, ground shake by earthquakes, impact loading from outburst and rapid flow of volcanic eruption materials and instability or overload slope by land use change and human infrastructural activities. The impacts of landslides include human casualties, economic losses, infrastructure damages and the change of physical environment and geomorphology. Landslide near the river occurs when the water due to high precipitation and runoff flows through unstable slopes of the riverside while groundwater increases in parallel with the river discharge.

Landslides on the upstream of dam reservoir obviously occur when reservoir impoundment has affected groundwater level of the upstream slope that penetrates into the susceptible soil layers which can fall down to the reservoir. The falling landslide mass into reservoir would significantly reduce the reservoir capacity. A particular case of landslide near the dam reservoir is chosen to analyze the cause and mechanism of such landslide which affect the service and sustainability of reservoir as water resource for human and agriculture needs.

The study of landslide near reservoir could be carried out by slope-stability analysis approach and landslide dynamics approach. Slope-stability analysis is to study whether or not a slope failure occurs. It is also the main tool for the study of landslide initiation, while landslide dynamics is to study landslide mobility after failure⁶. The study of shear strength reduction in landslide mass is important as part of the landslide dynamics science which covers mobility after failure, associated with landslide hazard level, risk assessment, landslide velocity and affected area. In this paper, the shear strength reduction in progress of shear displacement on the landslide near dam reservoir is investigated by means of ring shear tests.

2. Materials and Methods

2.1. Impoundment of Aratozawa reservoir and the 2008 large-scale landslide

The Aratozawa dam (Fig. 1) is located in the southeast of Mount Kurikoma in the Iwate-Miyagi Prefecture of Japan. The height of Aratozawa dam is 74.4 m and length of about 414 m with the geographical position at 38°53’4.98’’ of north latitude and 140°51’42.93’’ of east longitude.



Fig. 1. Aratozawa dam and reservoir in Miyagi Prefecture of Japan (photo taken in June 2013)

According to Ministry of Land, Infrastructure and Transport of Japan, this dam was built in 1983 and categorized as rock-fill dam with central core. The main purpose of the Aratozawa dam and reservoir are flood control and

irrigation. The maximum water level at all times in Aratozawa reservoir reach 275.4 m above sea level and the minimum water level is about 241.1 m above sea level. The catchment area of the Aratozawa reservoir is approximately 20.4 km² with the total water storage capacity design of about 14,130,000 m³. The daily inflow and outflow rate of Aratozawa reservoir are fluctuated in terms of dam purpose since the dam started to operate in 1998.

The deep-seated large-scale landslide on the upstream of Aratozawa reservoir occurred shortly after the Iwate-Miyagi inland earthquake of magnitude 7.2 hit the Ohu Mountains on 14 June 2008. Aratozawa landslide has gentle gradient of about 2-4 degree at a depth varied from about 150 m near the head scarp (crown) to 70 m at the main body slide^{2,4}. In addition, Aratozawa landslide resulted in the movement of massive blocks and ridges of 1,300 m in length and 900 m wide with sediment volume of more than 67 million cubic meters that slipped about 320 m. The toe part of landslide was directed into the dam reservoir and caused tsunami wave of about 2.4 m³. Because of the geometry and sediment volume, the landslide near Aratozawa dam was stated to be the largest catastrophic landslide in the last 100 years in Japan⁴.

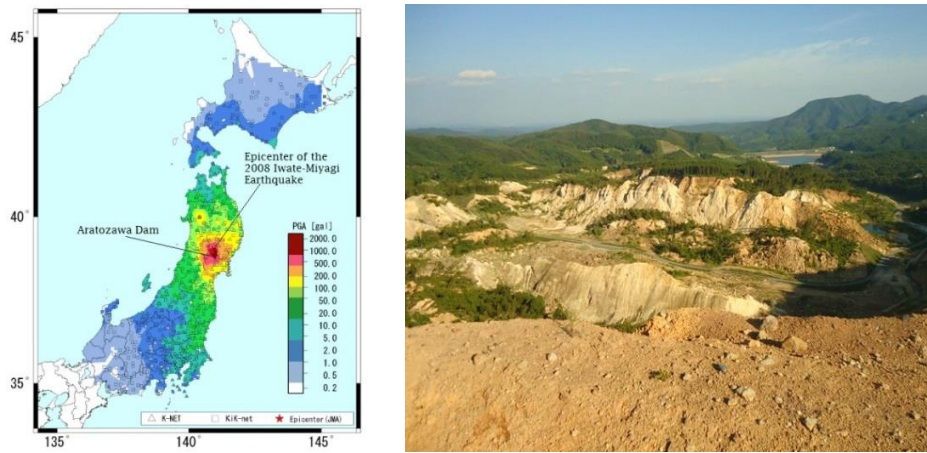


Fig. 2. Distribution of peak ground acceleration of the 2008 Iwate-Miyagi Nairiku earthquake (K-Net and KiK-Net data from NIED, Japan) and view of Aratozawa landslide from head scarp (photo taken in June 2013)

Aratozawa landslide was mainly triggered by an earthquake with the seismic peak ground acceleration of more than 1,000 gal as reported by several researchers. However, the possibility of reactivated landslides in surrounding terrains near Aratozawa reservoir as the dynamic-geomorphologic movement in Ohu mountainous area within a period of a hundred years⁵ is strongly relevant with water fluctuation in the reservoir as other triggering factors. Based on the observed data provided by Ministry of Land, Infrastructure and Transport of Japan, the daily elevation of Aratozawa reservoir since it began to operate in 1998 up to 2011 can be seen as provided Fig. 3. It could be stated that the fluctuation rate of Aratozawa reservoir is significant in terms of dam purpose.

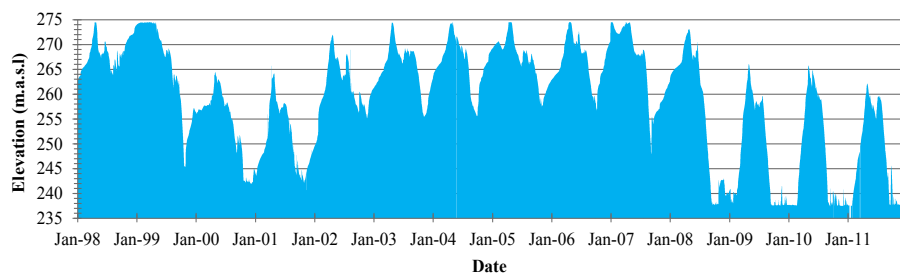


Fig. 3. The daily elevation of Aratozawa reservoir in 1998-2011

Since November 2007 until June 2008, where landslide occurred, the inflow-outflow difference observed in the positive trend where the water elevation in the reservoir had increased continuously of about 20 m up to elevation

273 m. The cumulative different of inflow-outflow discharge rate impounded in the reservoir reached 90 m³/s (7.77 million cubic meters) in May 2008 just about one month before landslide event occurred. However, there was drawdown discharge of the reservoir in early June that made the discharge rate decreased to 50 m³/s (4.32 million cubic meters) with water elevation stands about 268 m.

The site investigation was conducted in autumn 2012 and summer 2013. Disturbed samples were taken from Aratozawa landslide area to be tested in laboratory using ring shear apparatus. From the observation and grain size distribution test result, sample from the secondary collapse zone (Fig. 4) was considered as the finest layer from overall Aratozawa landslide samples. The finest soil sample is the key to study the shear strength reduction of suspected slip surface in progress of shear displacement of Aratozawa landslide.

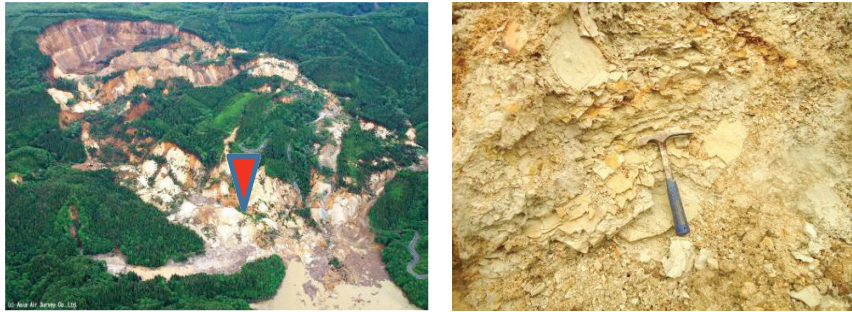


Fig. 4. Sample location (aerial photo from Asia Air Survey Co. Ltd., sampling taken in Nov 2012)

Table 1. Grain size distribution of the exposed finest layer of secondary collapse zone in Aratozawa landslide.

Specification	Volcanic tuff
Specific gravity	2.061
Average particle size, D50 (μm)	21.733
Effective particle size, D10 (μm)	3.885
Coefficient of uniformity	6.608

2.2. Undrained dynamic loading ring shear apparatus

Ring shear apparatus in the Disaster Prevention Research Institute (DPRI) of Kyoto University has been developed since 1984 in order to address the needs of undrained shear tests with pore pressures monitoring and sliding surface observation at large shear displacement^{7,8,9}. A series of ring shear apparatus have been used to study and analyze the initiation of soil failure, residual shear resistance as well as post-failure motion and deformation characteristics in large displacement¹⁰.

The ring shear apparatus ICL-2 has five components: (1) Undrained ring shear box and loading system; (2) Main control unit; (3) Monitoring control unit; (4) Separated servo generator with back pressure unit; and (5) Vacuum pump de-aired water system. The loading concept of ICL-2 does not incorporate loading frame. The central axis pulled by loading piston which is controlled by servo valve (SV) using feedback signal from load cell (N) through servo amplifier (SA) (Fig.5). The installation of back pressure machine for pore-water pressure was integrated with the servo generator controlled with oil pump like normal stress loading system⁴.

Table 2. Features of the undrained dynamic loading ring shear apparatus ICL-2 [10].

Specification	Unit	Capacity
Shear box inner diameter	cm	10
Shear box outer diameter	cm	14.2
Max. height of sample	cm	5.2
Shear area	cm ²	79.79
Max. Normal stress	kPa	3,000
Max. Shear speed	kPa	50
Max. Pore-water pressure	kPa	3,000

The undrained cyclic loading tests and earthquake loading tests are conducted using ring shear apparatus ICL-2 version to explain the effect of shear strength reduction in progress of shear displacement on the landslide near Aratozawa dam reservoir from pre-failure state to the steady-state motion.

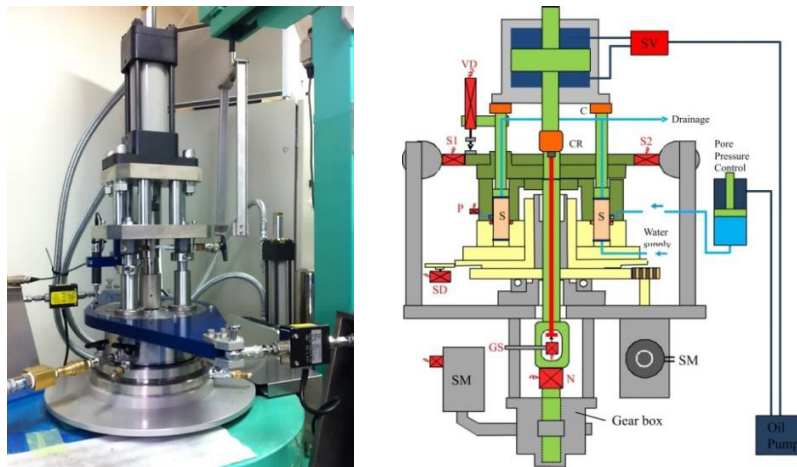


Fig. 5. Structure of the undrained ring shear box ICL-2 and its loading system (Sassa et al. 2014)

3. Shear Strength Reduction in Landslide Dynamics

The concept of shear strength reduction in progress of shear displacement⁵ is introduced to observe the critical state of landslide mass from the beginning of collapse, sliding and deposition stage. The shear strength reduction consists of four stages: (1) initial state, (2) pre-failure state, (3) transient state and (4) steady state. As shown in Fig. 6, the initial state represents the state when the soil stability stood under the peak friction coefficient ($\tan \phi_p$). The pre-failure state occurs when shear resistance reached peak friction coefficient due to heavy rainfall, groundwater rise, rapid drawdown, seismic loading from earthquakes or the combination of both. The critical shear displacement in the pre-failure state (DL) indicates the soil or slope failure and landslide occurrence.

The following stage is called the transient state which is transition from failure point to steady state. The pore pressure generation together with shear strength reduction will proceed in progress of shear displacement in transient state. The final stage called steady state in which the landslide mass still moves without any strength reduction. The transition stage from transient to steady state is marked with the critical shear displacement at the end of shear reduction (DU). All stages are assessed from the friction coefficient of landslide mass. In the condition of constant normal stress, the friction coefficient is represented as the shear resistance during shear loading.

Shear strength reduction in progress of shear displacement is observed through two kinds of tests: (1) cyclic shear test with high amplification in a high normal stress of 3 MPa; and (2) Iwate-Miyagi Nairiku earthquake load test

with high initial pore water pressure. Both tests were conducted in a high de-aired saturated samples and undrained condition where no pore water dissipation is allowed in order to observe pore pressure generation and shear strength reduction precisely.

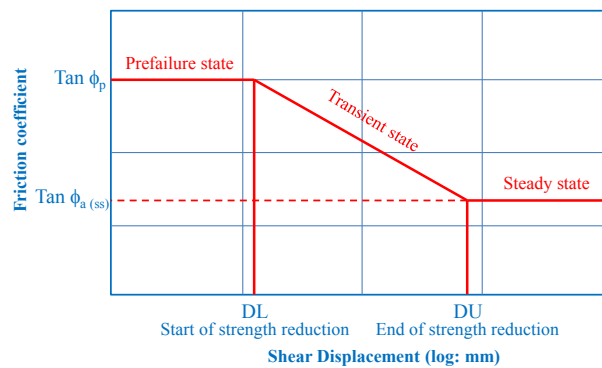


Fig. 6. Concept of shear strength reduction in progress of shear displacement (Sassa et al. 2010)

4. Results and Discussion

The cyclic shear test in undrained condition was conducted in order to observe the pore pressure generation and initiation of failure motion due to the cyclic shear load like earthquake-pattern in a slow speed. Through cyclic shear load, the shear displacement pattern and shear strength reduction of Aratozawa samples from pre-failure state to steady state could be obtained. Fig. 7 shows the result of the undrained cyclic loading test for secondary collapse zone sample. The cyclic loading was conducted with 300 kPa of initial amplitude, 4 cycles of amplification, 5 constant cycles and 5 cycles of attenuation. Pore-water pressure was generated more than 1000 kPa during constant cycles where shear resistance rapidly lost its strength. When the pore pressure reached about 1650 kPa, the shear displacement was accelerated in terms of shear strength reduction. The shear displacement reached above 8 m because at elapsed time of 180 second, the shear resistance decreased on the transient stage.

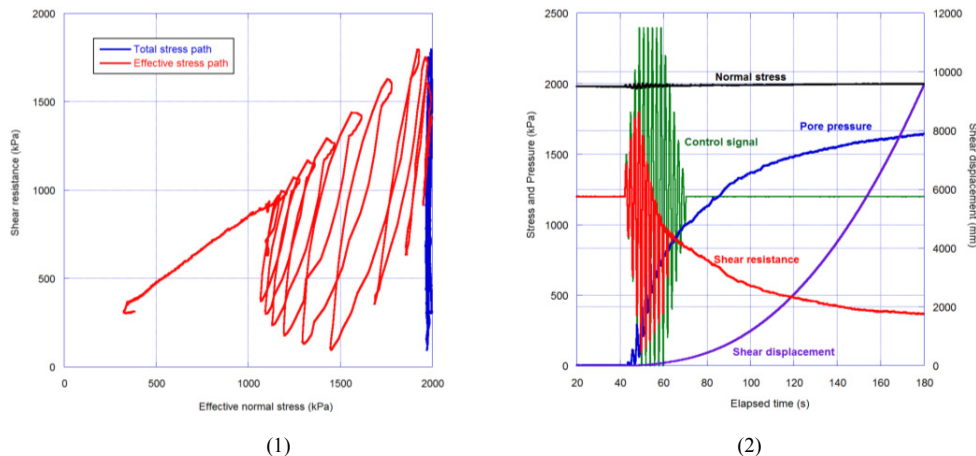


Fig. 7. Cyclic load of secondary collapse zone of Aratozawa landslide: (1) Effective stress path (2) Time series

From the earthquake wave test using ring shear apparatus ICL-2, the 2008 Iwate-Miyagi Nairiku earthquake have not fully triggered the pore pressure generation and even the shear displacement increased, but it was very small and not significant¹⁰. Based on the results of earthquake simulation and pore pressure controlled tests of Aratozawa samples, the deep and large-scale landslide on the upstream of Aratozawa landslide occurred through the combined

triggering factors of high initial pore-pressure and the 2008 Iwate-Nairiku earthquake. The high initial pore-pressure came from slow continuous groundwater rise that was in line with water impoundment in the reservoir along 6 months before landslide event (November 2007 up to May 2008).

The Iwate-Miyagi Nairiku inland earthquake was applied to the undrained shear box with the assumed slip surface about 22 degree. The effective stress path and wave time series of combined test applied in Atzw SCZ secondary collapse zone is shown in Fig. 8. It can be seen that pore water pressure increased rapidly due to wave loading and reached its peak of about 2300 kPa while the shear strength decreased rapidly in progress of mobilized shear displacement. The steady state shear resistance was reached after 10 m moving displacement when the pore pressure seems to be constant in a high value.

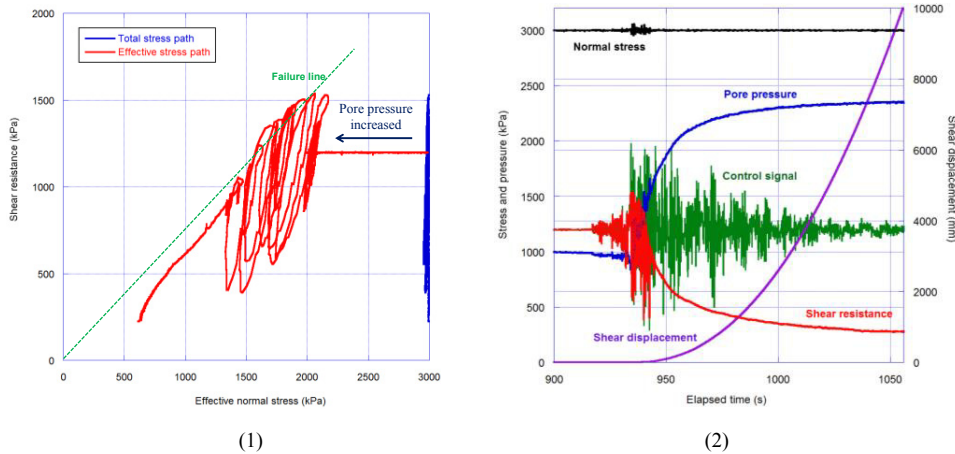


Fig. 8. The 2008 Iwate-Miyagi earthquake load of secondary collapse zone of Aratozawa landslide: (1) Effective stress path (2) Time series

The effective stress reduction during Iwate-Miyagi inland earthquake in 2008 is the key issue of Aratozawa landslide³. Fig. 9 shows the graph of shear strength reduction during cyclic loading on sample from exposed collapse zone. The transient state started at DL = 5 mm and ended at DU = 1200 mm or more with the steady state shear resistance started from 240 kPa. This implies that the collapse zone has vulnerable in acceleration motion and long traveling shear displacement. Even at 10 m height in shear displacement, the trend of shear resistance was likely to diminish in several meters until there was a constant steady state shear resistance.

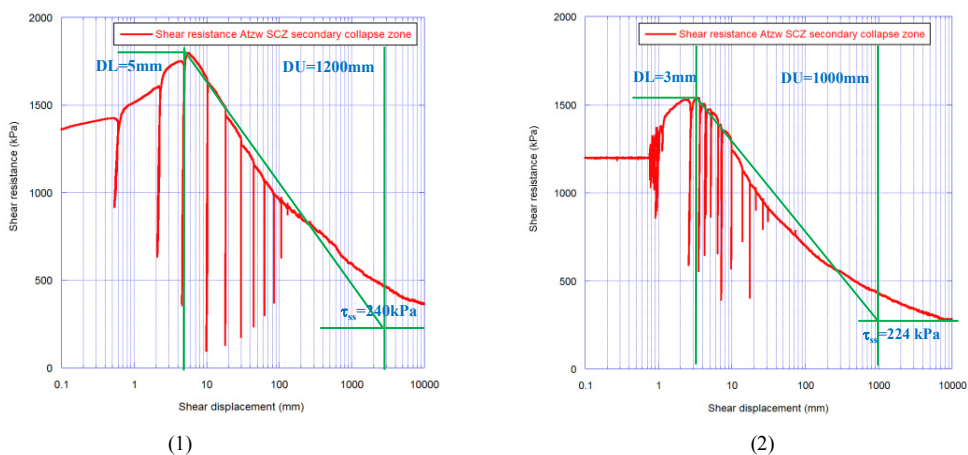


Fig. 9. Shear strength reduction of secondary collapse zone of Aratozawa landslide: (1) Cyclic load (2) The 2008 Iwate-Miyagi earthquake load

5. Conclusion

Shear strength reduction in progress of shear displacement on the landslide near dam reservoir was conducted in this research using ring shear apparatus. The undrained cyclic loading tests and earthquake loading tests were conducted to explain the shear strength reduction in progress of shear displacement from pre-failure state to the steady-state motion. The tests results show that the sample from secondary collapse zone is the weakest specimen which is vulnerable to be mobilized in a long distance of shear displacement. In addition, the ring shear tests results indicate that the rapid shear strength reduction of landslide mass was mainly caused by initial high pore pressure and exacerbated by the 2008 Iwate-Miyagi inland earthquake as a main shock in the case of deep and large-scale landslide near Aratozawa dam reservoir. The initial high pore pressure appeared due to the cumulative water impoundment in the Aratozawa reservoir.

A huge landslide near the upstream area of Aratozawa dam reservoir is an important case to study landslide risk assessment towards the sustainability of reservoir. Understanding the landslide risk near reservoir by investigating through survey and laboratory experiments, as shown in this paper, is a fundamental step to assess the landslide mechanism and its impacts to the reservoir. The results of shear strength reduction in a progress of shear displacement of Aratozawa landslide are essential input for further study that deals with disaster risk management and evaluation of reservoir particularly in Aratozawa Dam and generally to all dams in the world.

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